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ACCOUNTING OF NUCLEON CORRELATIONS FOR STUDY OF MOMENTUM DISTRIBUTIONS IN NUCLEI*

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Nuclon momentum distributions of the ^{12}C, ^{16}O, ^{40}Ca, ^{56}Fe, ^{208}Pb and some light neutron-rich nuclei are calculated by a model using the natural orbital representation and the experimental data for the momentum distribution of the ^{4}He nucleus. The model allows realistic momentum distributions to be obtained using only hole-state natural orbitals or mean-field single-particle wave functions as a good approximation to them. To demonstrate the model, different sets of wave functions were employed and the predictions were compared with the available empirical data and other theoretical results.

Учет нуклонных корреляций для изучения импульсных распределений в ядрах

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Импульсные распределения нуклонов в ядрах ^{12}C, ^{16}O, ^{40}Ca, ^{56}Fe, ^{208}Pb и в некоторых легких нейтронно-избыточных ядрах рассчитаны с помощью модели, которая использует представление естественных орбиталей и экспериментальные данные об импульсном распределении ядра ^{4}He. Модель позволяет получить реалистические импульсные распределения, используя только естественные орбитали дырочных состояний либо одночастичные волновые функции среднего поля как хорошее приближение. Чтобы продемонстрировать возможности модели, использовались разные наборы волновых функций и были проведены сравнения с имеющимися экспериментальными данными и другими теоретическими результатами.

1. Introduction

The systematic investigations of the nucleon momentum distributions in nuclei extend the scope of the nuclear ground-state theory. The experimental situation in recent years makes it possible to study quantities such as: the nucleon momentum distribution $n(k)$ which is specifically related to the processes like the $(p, 2p)$, $(e, e'p)$ and (e, e') reactions, the

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nuclear photoeffect, meson absorption by nuclei, inclusive proton production in proton-nucleus collisions, and even some phenomena at low energies such as giant multipole resonances.

The main characteristic feature of the nucleon momentum distribution obtained by various correlation methods [1—7] is the existence of high-momentum components, for momenta $k > 2$ fm^{-1}, due to the presence of short-range and tensor nucleon correlations. We emphasize also the fact that theoretical results of the methods mentioned above as well as experimental data for $n(k)$ obtained by the y-scaling analysis of inclusive (e, e') experiments [8,9] confirm the conclusion that the high-momentum behaviour of the nucleon momentum distribution ($n(k)/A$ at $k > 2$ fm^{-1}) is almost the same for nuclei with mass number $A = 2$, 3, 4, 12, 16, 40, 56 and for nuclear matter (see [2], p.139). More generally, the above property of $n(k)$ is true for all nuclei with $A \geq 4$, and ^{4}He is the lightest nuclear system that exhibits the correlation effects via the high-momentum components of the nucleon momentum distribution. Since the magnitude of the high-momentum tail is proportional to the number of particles, this effect is associated with the nuclear interior rather than with the nuclear surface. This allows us to suggest a practical method to calculate the nucleon momentum distribution for nuclei heavier than ^{4}He (e.g., ^{12}C, ^{16}O, ^{40}Ca, ^{56}Fe, and ^{208}Pb) from that one of ^{4}He which is already known from the experimental data. In general, the knowledge of the momentum distribution for any nucleus is important for calculations of cross sections of various kinds of nuclear reactions.

In the last years the light exotic nuclei with $N/Z > 1$ are studing very intensively. The peculiarities of these nuclei start from $N/Z \approx 2$ when a deviation from the shell-model scheme of the nuclear levels is discovered (for instance, in ^{11}Be nucleus). In nuclei with $N/Z \approx 3$ (^{8}He, ^{11}Li) the neutron «halo» and associated anomalously large rms radius are observed. In the region $N/Z \approx 2.5$ (nucleus ^{10}Li) the nuclear structure is established as a core of $(A - 1)$-particles in the ground state plus loosely-bound extra neutron. These peculiarities of the nuclei which have not been identified before show that the nuclear physics began investigating regions of nuclei with new feature. This induces our calculations on exotic nuclei momentum distribution based on the method suggested recently [10].

2. The Model

The model uses the transparency of the single-particle picture existing within the framework of the given correlation method by means of the natural orbital representation [11], where the proton momentum distribution normalized to unity has the form:

$$n(k) = \frac{1}{4\pi Z} \sum_{nlj} (2j + 1)\, \lambda_{nlj}\, |\tilde{R}_{nlj}(k)|^2. \qquad (1)$$

In (1) $\tilde{R}_{nlj}(k)$ is the radial part of the natural orbital in the momentum space, λ_{nlj} is the natural occupation number for the state with quantum numbers (n, l, j) and

$$\sum_{nlj} (2j+1)\,\lambda_{nlj} = Z. \tag{2}$$

In the case of neutron momentum distribution Z has to be replaced by the number of the neutrons N. It was shown by the Jastrow correlation method (JCM) [6] that the high-momentum components of the total $n(k)$ caused by short-range correlations are almost completely determined by the contributions of the particle-state natural orbitals. This fact, together with the approximate equality of the high-momentum tails of $n(k)$ for all nuclei with $A \geq 4$, allows us to make the main assumption of this work, namely, that the particle-state contributions to the momentum distributions are almost equal for all nuclei with $A \geq 4$. Using the equality, we obtain the following general relation of the correlated proton momentum distribution of a nucleus (A, Z) with that one of the ^{4}He nucleus:

$$n^{A,Z}(k) = N\left[n^{^4\mathrm{He}}(k) + \frac{1}{4\pi}\left(\frac{1}{Z}\sum_{nlj}^{F_{A,Z}} (2j+1)\,\lambda_{nlj}^{A,Z}\,|\tilde{R}_{nlj}^{A,Z}(k)|^2 - \lambda_{1s_{1/2}}\,|\tilde{R}_{1s_{1/2}}^{^4\mathrm{He}}(k)|^2 \right)\right], \tag{3}$$

where

$$N = \left[1 + \frac{1}{Z}\sum_{nlj}^{F_{A,Z}} (2j+1)\,\lambda_{nlj}^{A,Z} - \lambda_{1s_{1/2}}^{^4\mathrm{He}} \right]^{-1}, \tag{4}$$

and $F_{A,Z}$ is the Fermi level for the nucleus (A, Z).

As shown in the previous papers the hole-state orbitals are almost unaffected by the short-range correlations and, therefore, the functions $\tilde{R}_{nlj}(k)$ can be replaced by the shell-model single-particle wave functions. The hole-state occupation numbers λ_{nlj} are close to unity within the JCM and we can set them equal to unity with good approximation. Thus the correlated nucleon momentum distribution can be calculated for any nucleus by means of the occupied shell-model wave functions and the momentum distribution of the ^{4}He nucleus which is taken from the experimental data [8] and which contains short-range correlation effects.

3. Calculations and Discussion

In this work we calculate the proton momentum distribution for nuclei ^{12}C, ^{16}O, ^{40}Ca, ^{56}Fe, ^{208}Pb and the nucleon momentum distributions for the Li,Be, B, and C isotopes. Empirical estimations for $n(k)$ are available for nuclei ^{12}C and ^{56}Fe [8].

In our calculations of proton momentum distributions we use two types of MFA single-particle wave functions: 1) single-particle wave functions obtained within the Hartree–Fock method by using Skyrme effective forces and 2) multiharmonic oscillator single-particle

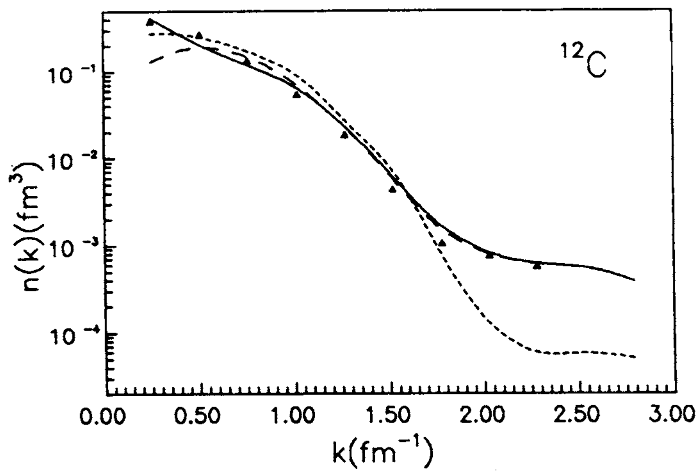

Fig.1. Proton momentum distribution $n(k)$ versus k of ^{12}C. Calculations by using single-particle wave functions from the multiharmonic oscillator shell model [13] are presented by solid line; and those by using the Hartree–Fock single-particle wave functions, by long-dashed line. The short-dashed line is $n(k)$ calculated in the Jastrow correlation method [6]. The solid triangles represent the data from [8]. The normalization is: $\int n(k)\, d^3 = 1$.

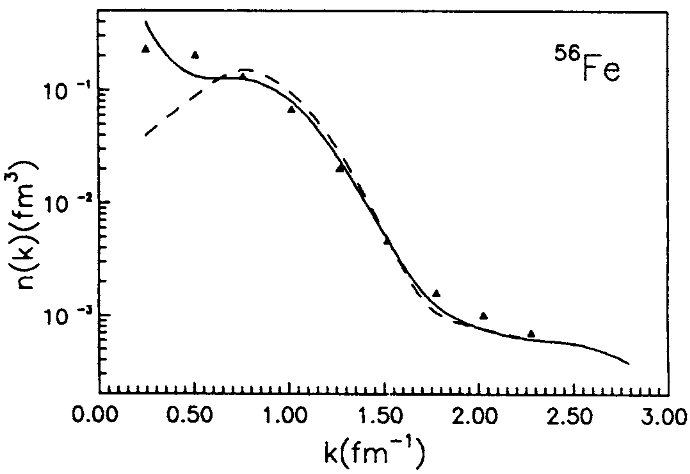

Fig.2. Proton momentum distribution $n(k)$ versus k of ^{56}Fe. Calculations by using single-particle wave functions from the multiharmonic oscillator shell model [13] are presented by solid line; and those by using the Hartree–Fock single-particle wave functions, by long-dashed line. The solid triangles represent the empirical data from [8]. The normalization is as in Fig.1.

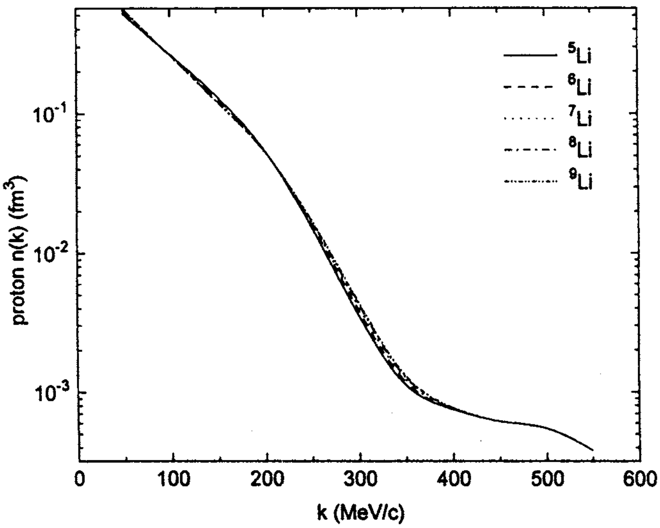

Fig.3. Proton momentum distribution in Li isotopes obtained by using harmonic-oscillator s.p. wave functions with $\hbar\omega$ defined by Eq.(5). The normalization is as in Fig.1

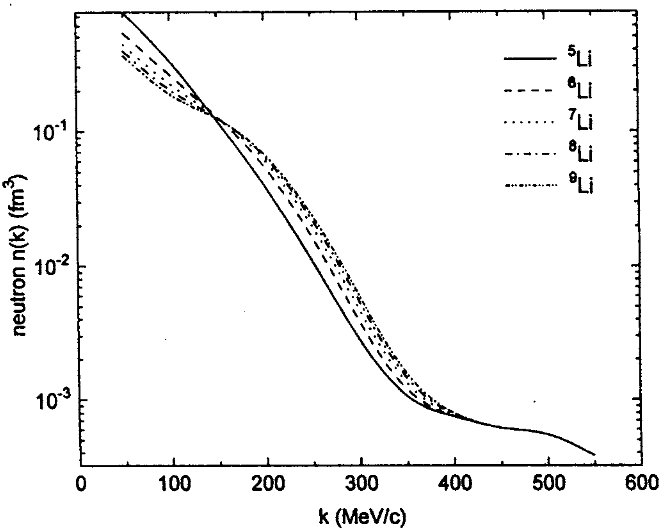

Fig.4. Neutron momentum distribution in Li isotopes obtained by using harmonic-oscillator s.p. wave functions with $\hbar\omega$ defined by Eq.(5). The normalization is as in Fig.1.

wave functions (with different values of the oscillator parameter for each state) which lead to a simultaneous description of ground-state radii and binding energies [12,13]. In addition to [13], in our calculations the multiharmonic oscillator s.p. wave functions are orthonormalized. In order to calculate the nucleon momentum distributions of the exotic nuclei we use harmonic-oscillator single-particle wave functions with an oscillator parameter which is A as well as N and Z dependent. This parameter gives, in principle, an estimate of the lowest energy level spacing and its variation with the number of the neutrons and protons. It represents also the average trend in the variation of the shape of the self-consistent nucleon-nucleus potential as a function of N and Z. In [14] an expression for $\hbar\omega$ as a function of N and Z is determined based on a formula for the nucleon charge radius which was proposed in [15] reproducing well the experimentally available RMS charge radii and the isotopic shifts of some even-even nuclei. It has the form:

$$\hbar\omega = 38.6A^{-1/3}[1 + 1.646A^{-1} - 0.191(N-Z)\,A^{-1}]^{-2}. \tag{5}$$

One can see from Figs.1 and 2 that the use of the single-particle wave functions from the multiharmonic oscillator shell model leads to better description of the experimental data for the central part of the momentum distribution than the use of the Hartree–Fock single-particle wave functions. In both cases the main deviations from the experimental data are for small momenta ($k \leq 0.5$ fm^{-1}). They are larger in the case when the Hartree–Fock s.p. wave functions are used and this is a common feature of the results for all nuclei considered. This is due to the well-known fact [16] that the Hartree–Fock method cannot give a realistic wave function for the 1s state in the ^{4}He nucleus. Namely this function ($\tilde{R}^{^4\mathrm{He}}_{1s_{1/2}}(k)$) takes part in the expression for $n(k)$ (Eq.(7)) in all nuclei. Both types of s.p. wave functions, however, give similar results for the middle part as well as for the tail of the momentum distribution in all cases considered. Concerning the exotic nuclei one can see from Fig.3 that all Li isotopes have almost the same proton momentum distributions. The small difference comes from the different values of $\hbar\omega = \hbar\omega(A, Z, N)$. The neutron momentum distributions of the same isotopes are presented in Fig 4.

The comparison of the results obtained by using different mean-field single-particle wave functions can be useful for the proper choice of the latter in the applications of the model to practical calculations of $n(k)$ in cases when the knowledge of this quantity is necessary.

4. Summary

Suggesting a practical method for realistic calculations of the nucleon momentum distribution in light, medium and heavy nuclei, we would like to test whether the high-momentum tail of the momentum distribution for any nucleus can be approximated by that for ^{4}He. We also check to what extent this approximation affects the central part of the momentum distribution. The numerical results in this work confirm to a great extent the abilities of the suggested correlation model to give realistic estimations for the proton momentum distribution in ^{12}C and ^{56}Fe and to predict the behaviour of $n(k)$ in ^{16}O, ^{40}Ca, and ^{208}Pb nuclei. They are in agreement with the results for the proton momentum distribution in ^{16}O and ^{40}Ca obtained within other theoretical methods in which the correlation effects are incorporated using nuclear matter results and with some empirical data for ^{12}C and ^{56}Fe obtained using the y-scaling method. We also make predictions for the proton and neutron momentum distributions of exotic nuclei. The knowledge of the realistic momentum distributions obtained in this work would allow us to describe in a similar way as it is done in [17] the quantities which are directly measurable in processes of particle scattering by nuclei.

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